Developing Web-based Digital Twin for Industrial Cyber-physical Systems*

Sergey Konstantinov, Fadi Assad, Wajid Azam, Daniel Vera, Bilal Ahmad, Robert Harrison
Automation Systems, Warwick Manufacturing Group (WMG)
University of Warwick
Coventry, United Kingdom
s.konstantinov@warwick.ac.uk

***Abstract*—Modern manufacturing relies heavily on digital technologies, and the recent changes in the manufacturing environment are the reflection of the advancements in information and communication technologies. Web-based Digital Twin (WDT) will constitute the future of manufacturing giving a greater potential of process/product data interaction, where Digital Twin functions on a web browser and connects to its Physical Twin to exchange data. To this end, the research work on WDT still in the first stages. Therefore, the current paper presents a framework for developing WDT taking into account the possibility of utilising WDT for education, research and industrial applications. A case study adopted from a mini-scale assembly line is used to illustrate the proposed concept.**

***Index Terms*—web-based digital twin, manufacturing systems, digital manufacturing, industrial cyber-physical systems**

I. Introduction

Industrial technology evolves to respond to market requirements in terms of high productivity and shortening the products/services time-to-market. The current era of manufacturing is smart manufacturing enabled by the advancements in the field of Information and Communication Technologies (ICTs) and characterised by the digitalisation of the manufacturing/production system and its planned outcomes whether services or products. The recent iconic technology that is the cornerstone of the cyber-physical systems is the digital twin (DT). DT promises to enable the fast reconfiguration and recommissioning of the automated systems, which yields a shorter time and lower cost [1].

On the other hand, it can be noticed that there is a trend of migrating software applications to web-based environments. One reason is the high-speed connectivity which guarantees quick data transfer, and the second reason is the availability of applications' building infrastructure on the cloud. For instance, the applications built in the .NET environment can be migrated to the Windows Azure cloud. This way, the software application relies on the processing resources available on the cloud. The third reason is the business model associated with the application producer in terms of marketing, application distribution, copyrights, customer support and future development. To keep manufacturing industry up-to-date with these changes, it is necessary to move to the web-based digital twin. Another important implication of this major step is the influence of DT on the dynamics of decision making. Digital twin technology is applicable when it comes to decision making in production and logistics [2], thus, increasing data visibility, transferability and transparency will yield an improved and timely decision making.

For Industry 4.0 to progress, reference architectures have to be structured [3]. Therefore, the current work introduces a framework of building web-based digital twin (WDT) contributing to the ongoing academic and industrial research on digital twin development. The aim is to take advantage of web browsers availability which allows more involved parties to engage in the system configuration and monitoring. Thus, the real-time data can be visualised and timely decisions are made in correspondence. The remainder of this paper is organised as follows: Section II reviews the research carried on web-based technologies for manufacturing systems and the latest digital twin advancements. Section III illustrates the authors' proposed WDT architecture, tools and applicability. In Section IV, a case study demonstrates the proposed concept, and Section V concludes the paper.

II. State of the art

A. Web-based manufacturing

The term "web-based manufacturing" can be detected in literature for both the production system and the product. The research in this area is abundant and serves the purpose of enabling "distributed manufacturing" and decentralisation by sharing the data related to the production system including logistics and manufacturing system. However, it is necessary to observe some of the changes commenced following the introduction of Industry 4.0 in 2011, especially concerning manufacturing systems.

The movement to create web-based collaborative systems in manufacturing started following the introduction of the Web that took place in 1993 [4]. Tsai and Lin [5] introduced the architecture of a web-based distributed manufacturing control system (MCS) along with proposed mechanisms for improving the system's performance. Chung and Peng [6] proposed and implemented a web-based tools and machine selection system (WTMSS) based on the belief that the use of such systems in web-based environments can reduce costs. In [7], web-based manufacturing is perceived as an enabler of collaborative manufacturing that closes the gap between off-line simulation

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and monitoring, therefore, a framework of linking the factory network to the Internet is introduced. A detailed review of the web-based manufacturing status before Industry 4.0 is introduced in [8] where it was indicated that web-based manufacturing will have a positive role in the elimination of interoperability problems, the effective data transfer in the form of XML files, and the collaborative planning and control of production.

Following the emergence of Industry 4.0, there is a tendency to build the required manufacturing applications in the cloud as the connectivity and data transferability are facilitated. Ferrer et al [9] proposed an approach of deploying industrial devices that use the Internet of Things (IoT) technology with functionalities provided by web-enabled services. In particular, for Cloud Computing (CC), it can provide the environment for deploying applications at the levels of Software as a Service (SaaS) and Platform as a Service (PaaS) [10]. Wu et al [11] believe that semantic web-based manufacturing supported by cloud-based manufacturing (CBM) allows a great opportunity of automating manufacturing processes.

B. Web applications for digital twin/digital shadow

The digital twin is a virtual/digital model that exchanges data with its physical counterpart in two directions [12]. Being a model whose function is to simulate a certain behaviour/response, it is necessary to understand how the web environment suits simulation.

Web-based simulations help to overcome the compatibility problem, open-source development and creating graphical user interfaces [13]. At the time being, there is a significant tendency to convert simulation into a web-based technology. In order for physical systems to be integrated into these intelligent cloud simulation platforms by means of IoT, they have to be modelled as digital twins [14]. Web applications grant the user the ability to interact with the cyber-physical system (CPS) without installing any additional software in addition to the advantages of low cost and high availability [15]. Liebenberg and Jarke [16] believe that the production sector has not taken the total advantage of the web application domains. Therefore, a prototype for a node of the "Internet of Production" research cluster is developed with a web interface seeking to provide a set of requirements by using digital shadows. In a digital twin based service-oriented application, Padovano et al [17] state that web-based services constitute a two-way channel that links human with machine. Seeking to deal with multiple devices and a variety of operating systems, the digital twin is built in HTML-5 application in [18] so that the automatic configuration and programming of the autonomous robotic systems becomes easier. Aiming at further virtualisation of the manufacturing resources in addition to creating an event-driven distributed control, a prototype of web-based remote control of ICPS (Industrial Cyber-Physical System)-based digital twin is introduced in [19]. Khrueangsakun et al in [20] introduced a concept of web-based visualisation and control of robotic arm using WebGL and web socket for the communication with the robot controller. The robot virtual model was created using Blender and further handled by WebGL using two website integrated engines: "Engine core" and "Engine API (Application Programming Interface)".

C. Summary

The literature shows that the movement to integrate the up-to-date manufacturing technologies in the web environment has never stopped. Thus, there is a remarkable need to lay out the guidelines of building web-based digital twin. Prior to the introduction of Industry 4.0, the scientific community put a good effort into establishing functional web-based manufacturing architectures. Later, their implementation has become easier as its communication and information requirements are more obtainable. In line with this, the current work establishes the essential guidelines with an industrial application adopted from a mini-scale assembly line.

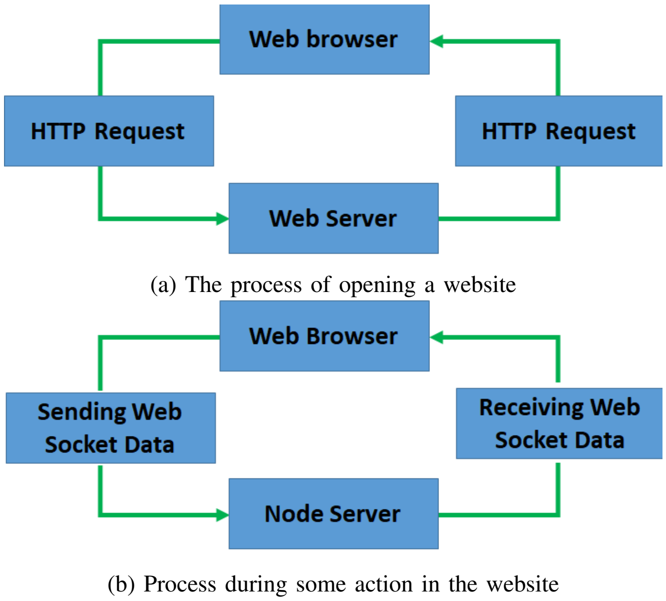
III. TOWARDS WEB-BASED DIGITAL TWIN

A. Basic concepts

Lee et al [21] introduced the 5C architecture of CPS where the levels (from base to top) are: Smart Connection Level, Data-to-Information Conversion Level, Cyber Level, Cognition Level and Configuration Level. Based on this, Redelinghuys et al [3] identified an architecture of six layers for constructing the digital twin: Layers 1 and 2: physical twin; Layer 3: local data repositories; Layer 4: IoT gateway; Layer 5: cloud based information repositories; Layer 6: emulation and simulation. DT should possess the following features: networking devices; synchronisation; multi-communication environment; data storage; data analysis; information selection; pattern identification; self adjustment; predictive analytics; perspective analytics; optimisation; closed loop feedback; simulation. [22], [23]. The authors define Web-based Digital Twin (WDT) as a "virtual entity that provides access to the virtual model of a certain asset of the cyber-physical system allowing data exchange with the physical entity through a web interface, and changing its configuration". The main environment of the 3D model and dynamic visualisation of the WDT framework is built on WebGL (Web Graphics Library). WebGL is a standard for enabling interactive 3D graphics on a Web-browser based on JavaScript programming language[1].

To enable the communication between the virtual model on a web browser and the Programmable Logical Controller (PLC), WebSocket library "Socket IO" and Node.js server were chosen. The communication is shown at the Fig. 1 [24]. This diagram was modified by substituting node server with the web server in Fig.1a. The diagram shows how the web browser sends an http request to web server to load the content in the web browser. In the presented case, the model will be hosted in a web server, and the browser will send an http request to load those files. Once loading from the web server is complete, the browser will connect to the Node.js server through web socket using Socket IO.

[1] https://developer.mozilla.org/en-US/docs/Web/API/WebGL_API



(a) The process of opening a website

(b) Process during some action in the website

Fig. 1: Node.js process during some action in the website [24]

Socket IO is a web socket-like library that enables real-time communication using the web client and web server[2]. Node.js is an open source event-driven development and runtime environment for scalable network applications[3].

B. Integration of web resources

A web application is defined as "any software application that depends on the World Wide Web for its correct execution" [5]. In their work published 2004, Wang et al [4] stated that the manufacturing systems available at that time are mainly for monitoring and off-line simulation. Meanwhile, deploying those systems requires dedicated software and cannot occur by means of the web browser. In the same period, in 2003, Yang et al [25] evaluated the status of web-based manufacturing indicating that the systems still prototypes for identifying their feasibility and futuristic potential.

Based on the literature, a web-based environment for both the product and the manufacturing system should provide: user engagement in a 3D visualisation with the ability of data sharing [4]; adaptability and efficiency in terms of responsiveness to the changes on shop floor [4]; an open architecture web-based distributed database and system modelling method [6], [25]; and reduced network traffic so that the decisions can be timely made [7].

C. WDT framework

The target is to build a manufacturing system's digital twin accessible via a web browser, where it can be connected to a stand-alone (physical or virtual) PLC, or to the physical system PLC, to replicate the behaviour of the system. This WDT can be uploaded to a server and can be accessed via a web browser anywhere in the world without special virtual engineering pre-installed software. One way to build such a digital twin on WebGL is to use JavaScript-based libraries and code the whole virtual system with its behaviour and animation. There are open-source JavaScript libraries e.g. babylon.js, Three.js, PlayConvas etc. which are able to provide the needed features. These libraries can easily be integrated with other JavaScript-based libraries which provide the necessary communication between the virtual web model and the physical system. However, using such libraries requires describing and coding the behaviour, actions, and movements of the virtual model actuators and other components. Doing so is quite demanding in terms of the significant amount of development time and skilled human resources. To reduce the development time Unity engine[4] was used for building the virtual model with its behaviour and communications, then exporting it to WebGL.

Another aim is to enable communication between the web browser virtual model and the Inputs-Outputs (IO) of a PLC. To achieve this, the OPC UA (Open Platform Communications Unified Architecture) [5] client-server platform was chosen. This platform has a significant number of PLC drivers, however, it can not directly communicate with a WebGL model. Therefore, Node.js was chosen as a bridge between the WebGL model and the OPC UA server. The virtual model is to be developed in Unity software from the imported CAD (Computer-Aided Design) components' files. The behaviour of each component is defined with C# scripts. Unity and OPC UA can be easily connected using OPC UA client libraries in the Unity model. However, after deploying the virtual model to WebGL and opening it with the web browser, OPC UA libraries are not available and communication cannot be established. Therefore, the third-party application (Socket IO client and server) was used to overcome this issue. It provides the communication between Unity WebGL model and OPC UA client.

Fig. 2 presents the WDT concept diagram and describes the approach taken to build it. The virtual model with its communication mapping (using .json file and Socket IO client) is built in Unity and further deployed on WebGL. After this, the web-based model can be connected to the stand alone PLC for Virtual Commissioning (VC) and tests or physical machine PLC for monitoring and Digital Shadow using Node.js communication bridge. As a result, the virtual model can change inputs' states at the PLC during VC. However, when the machine's PLC is connected and during the physical machine operation, it is not possible to change physical inputs. Therefore, it only possible to monitor the IO states and move the virtual machine according to the physical twin. Nevertheless, it is still possible to change PLC memory addresses, or include some maintenance, data storage & analytics, etc. applications in this architecture to exchange data with the virtual model during the physical machine run.

The proposed architecture can be used for teaching, research and industrial applications. For example, for the remote PLC

[2]https://socket.io/docs/v3
[3]https://nodejs.org/en/about/
[4]https://unity.com/
[5]https://opcfoundation.org/about/opc-technologies/opc-ua/

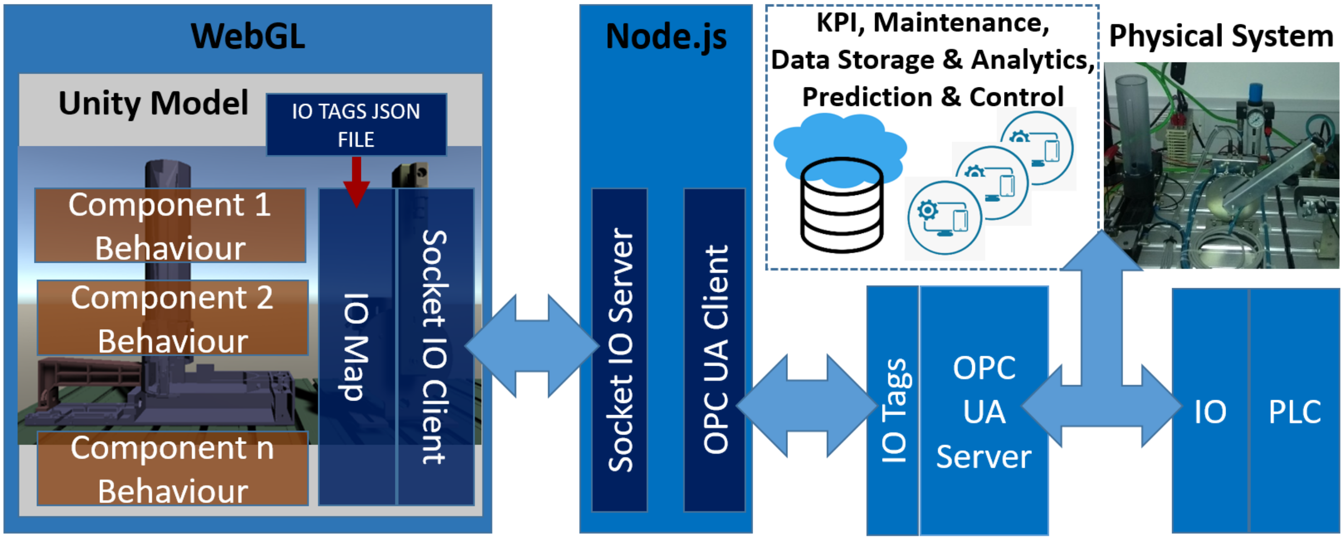


Fig. 2: Web-based Digital Twin architecture

programming teaching: students do not need a physical machine or expensive Virtual Engineering/ Virtual Commissioning software to represent a Digital Twin. The WDT model can be loaded at the host server and accessed via a web browser remotely from the student's laptops or from the classrooms. Students need only the virtual/physical PLC and the PLC programming application.

For industry, WDT can be used as a Virtual Commissioning tool to test the machine functionality before the physical machine is built. Also, WDT is valid for the monitoring and maintenance of the physical machine during the operation time. Further, WDT can act as a Digital Shadow and can be easily accessed from a web browser by the technical staff as well as by the management without installing specific Digital Twin/Shadow software from anywhere in the world. If the physical machine has specific software for KPI (Key Performance Indicators), maintenance and energy monitoring, the digital twin can be connected and involved in the loop for simulating the changes or testing the parameters during the physical machine runtime. So, the change can be validated during the operation phase before its application to the physical machine and without the machine disturbance.

IV. Case Study and Implementation

Station 1 of the Festo Modular Production System (MPS)[6] was chosen as a testbed for the case study implementation. The Festo modular test rig is designed for the representing and simulating real automated manufacturing processes, for research and education purposes. The Station 1 of the rig (Fig. 3.) consists of the workpiece cassette feeder hopper, pusher and swivel arm with vacuum gripper. When a part falls into the hopper, a sensor detects it and the pusher pushes the workpiece to the pick position. There is another sensor which detects the workpiece arrival, then the swivel arm rotates towards down the workpiece and picks the workpiece by a vacuum gripper. It then moves the part at the conveyor position which is the starting point of the Station 2 of the Rig. The virtual model of Festo Rig Station 1 was developed in Unity from imported CAD geometry files. The initial geometry was available in .wrl format only and had to be converted to one of the Unity readable formats, e.g. .3ds or .obj. The virtual model was assembled and the behavioural script (in C#) had to be assigned to each dynamic component. After this, Socket IO communication asset was added and communication with the Node.js server was established.

At the PLC side, Siemens S1200 was chosen for operating the model processes. PLC code was developed in the Siemens TIA (Totally Integrated Automation®) portal and communication to the controller was established using Ethernet IP. For the communication to Node.js, OPC UA channel with S1200 PLC drivers was created using KepServerEX®, IO tags had to be imported from the TIA portal IO table.

At the Unity side, PLC IOs were imported using IO Tags file in .json format and then mapped to the components. PLC outputs were mapped to the component's behaviour script to initiate movement actions and PLC inputs were mapped to monitor the actual positions of the component (e.g. Pusher retracted or Pusher extended). This mapping allows PLC to control the functionality of the virtual model according to the positions' feedback. When all components' geometry and behaviours were created, IO signals were mapped and Socket IO and PLC communication was defined, the model was tested for its functionality inside Unity using "play" feature. After the successful tests in Unity, the model was exported to WebGL and opened with the web browser (see Fig. 3). Communication with the PLC over OPC UA Kepware Server and Node.js was reestablished. The web model was successfully connected and once launched, the workpiece was dropped to the feeder and

[6]https://www.festo-didactic.com/int-en/learning-systems/mps-the-modular-production-system/stations/

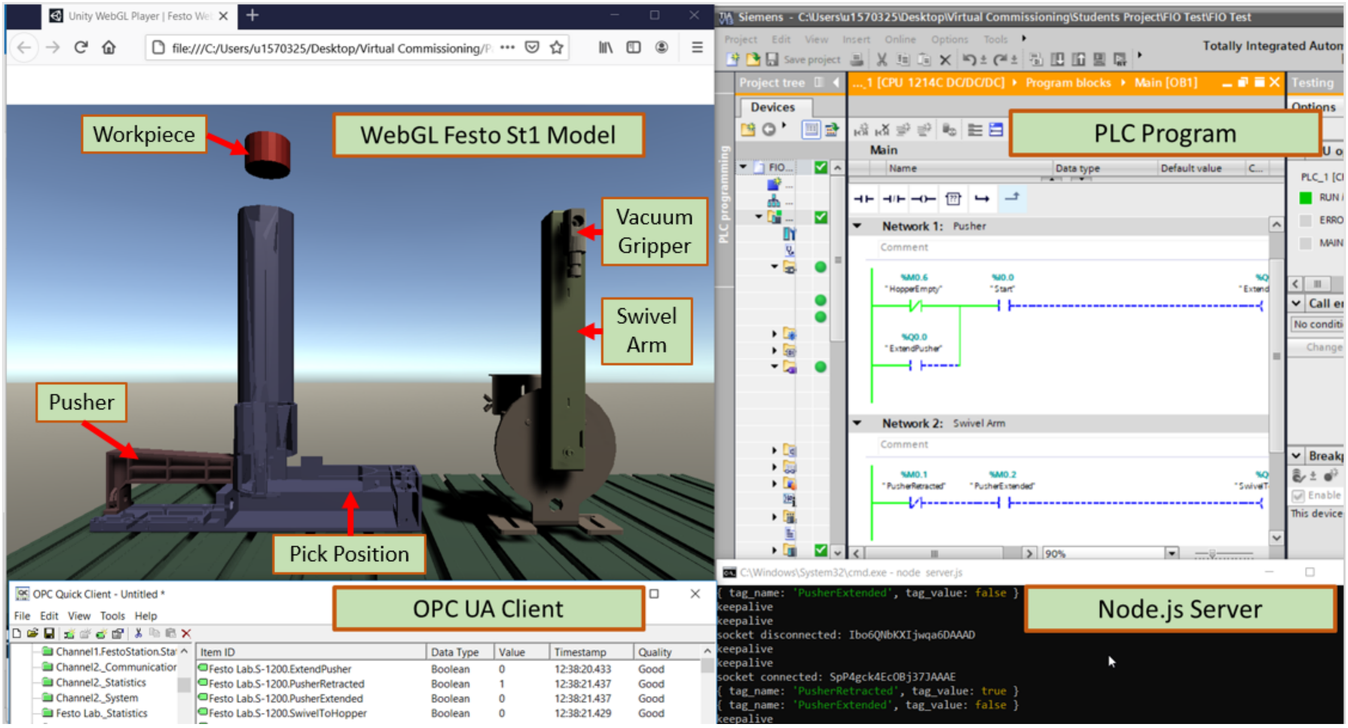


Fig. 3: Station 1 of FESTO rig web model operated by a PLC

moved by the pusher to the pick position. The position signals were switched to "Pusher retracted" from 'true' to 'false' and for "Pusher extended" from 'false' to 'true', and sent to the PLC via Socket IO and OPC UA servers. Thus, the web model and the WDT architecture proved their proper functionality.

The main goal of the paper was to validate the concept of the WDT development and its web-based model communication with a PLC. Putting these findings in the general context of CPS, and to clarify the current work contribution as a Digital Twin in the context of CPS, WDT capabilities are evaluated against the characteristics of DT in CPS introduced in [23] and previewed in Table I. The characteristics with the label "Achieved" currently exist in the implemented WDT. For those labelled "Ready", they are implementable using the proposed architecture, and will be the following target. The rest whose label is "Achievable" will need further software tools integration and/or coding. The case study showed that the current Web-based virtual model can be synchronised and connected to a PLC as well as to other devices or software tools, so the characteristics 1-3 were achieved. The WDT system architecture is ready to be connected to the data storage (4.) and data analytics (5.) applications. For example, the WDT model can be connected to SQL (Structured Query Language) server and DES (Discrete Event Simulation) tools. Those tools can select information (6.) and identify patterns (7.) once the suitable programming codes are developed. For further CPS integration, the proposed WDT architecture needs to be improved with the tools to achieve characteristics 8-13. This can be done using the same DES tools, MES (Manufacturing Execution Systems) and machine learning.

TABLE I: DT framework characteristics evaluation according to DT in CPS

Characteristic of DT in CPS	Achieved	Ready	Achievable
1. Networking Device	✓	-	-
2. Synchronisation	✓	-	-
3. Multi-communication environment	✓	-	-
4. Data storage	-	✓	-
5. Data analysis	-	✓	-
6. Information selection	-	✓	-
7. Pattern identification	-	✓	-
8. Self-adjustment	-	-	✓
9. Predictive analytics	-	-	✓
10. Prescriptive analytics	-	-	✓
11. Optimisation	-	-	✓
12. Closed loop feedback	-	-	✓
13. Simulation	-	-	✓

V. Conclusion and Outlook

The main objective of the paper is to demonstrate the proposed architecture and approach of enabling Web-based Digital Twin of the physical automation system which constitutes the basis of cyber-physical systems. Furthermore, it was important to prove that this concept is applicable, reliable and able to satisfy the current industrial needs. The case study showed an example of the WDT of the automation system, which was connected to a physical PLC via the proposed architecture. Unity was chosen as the virtual model development environment, however, it was necessary to do some modifications and use some third-party applications (such as Socket.io and Node.js) to enable the exported web-based model communication with the PLC via OPC UA.

The WDT communication with PLC and tests were successfully done, as the model can read and write signals to PLC. It is possible to exclude the OPC UA platform by using e.g. Kepware IoT Gateway and TCP IP. It is also further possible to use MQTT with publish/subscribe and event-based communication. However, the current architecture can be further improved by decreasing the communication system complexity and time delay. Future work will aim at enabling WDT's analytical and cognitive capabilities of simulation, optimisation and decision making.

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